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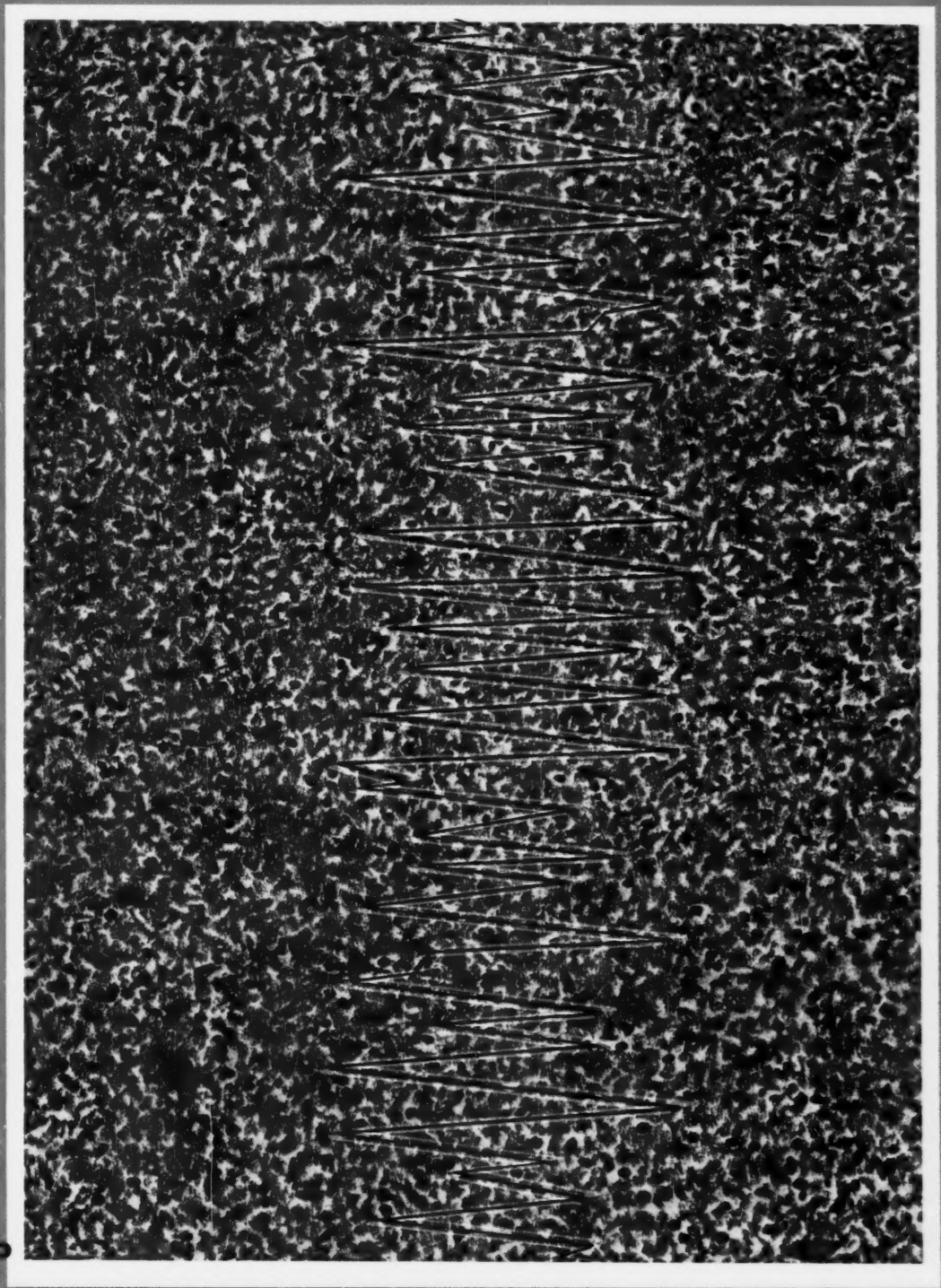

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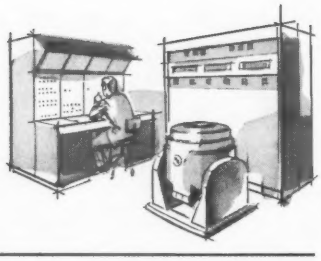

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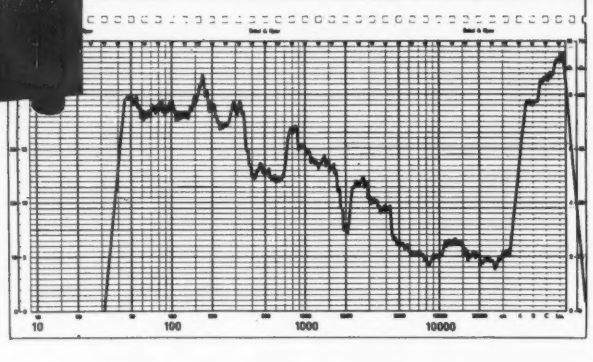

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OCTOBER 1960

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DYNAMIC AMPLIFICATION OF A TWO-DEGREE-OF-FREEDOM SYSTEM

by JOSEF S. PISTINER and HERBERT REISMANN
THE MARTIN COMPANY, DENVER DIVISION

ABSTRACT

A dynamic amplification factor of two (2) is frequently used by stress analysts as a rule of thumb. This investigation considers a two-degree-of-freedom system and shows that amplification factors due to a suddenly applied constant force may be arbitrarily large, their amplitude depending on the parameters of the system.

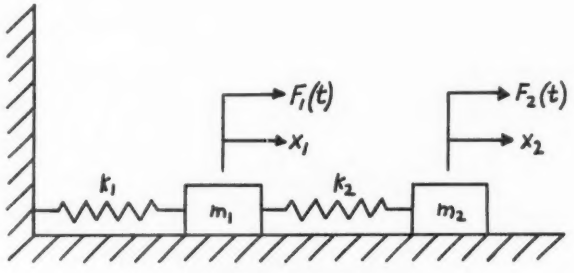
NOMENCLATURE

m	mass
k	spring constant
x	displacement
t	time
F	force
ω	frequency
A	dynamic amplification factor
u,f,g	frequency ratios
n,p,q,r	integers

INTRODUCTION

Even a cursory perusal of the engineering literature will reveal many investigations and discussions of the response of structures or mechanical systems to rapidly applied loadings. A series of articles by Roberts [1][1], [2], [3], deals with the response of a system idealized as having one degree of refedom. A major conclusion which the above-named and other authors [4], [5], obtain, is that for an elastic system having one degree of freedom, the maximum Dynamic Amplification factor (i.e. ratio of peak to static deflection) obtainable is never greater than two. An example of the response of a continuous system to a suddenly applied load is given by Timoshenko [6] He considers the response of an elastic bar to a force suddenly applied at one end. In this case the dynamic amplification turns out to be exactly two. Because these and similar results are well known, there appears to be a tendency among some stress analysts and designers to use an arbitrary amplification factor of two as a rule of thumb. For this reason we shall exhibit a spring-mass system with two degrees of freedom where a suddenly applied (constant) load will be shown to produce arbitrarily large amplification factors, their value depending upon the parameters of the system.

[1] Numbers in brackets refer to the references appended to this article.



TWO-DEGREE-OF-FREEDOM SYSTEM
FIGURE 1

STATEMENT AND SOLUTION OF PROBLEM

We shall consider a mechanical system constrained to move on a plane and comprised of two masses and two springs connected as shown in Figure 1. It should be noted that the springs k_1 and k_2 are assumed linearly elastic, and that the effect of friction is neglected. The forces F_1 and F_2 are acting on the masses m_1 and m_2, respectively.

The equations of motion, from Newton's law, are

$$m_1\ddot{x}_1 + k_1x_1 - k_2(x_2 - x_1) = F_1(t) \qquad (1)$$

$$m_2\ddot{x}_2 + k_2(x_2 - x_1) = F_2(t) \qquad (2)$$

The forces $F_1(t)$ and $F_2(t)$ are step functions of magnitude F, i.e.,

$$F_1(t) = F_2(t) = F \quad \text{for} \quad t > 0$$

$$= 0 \quad \text{for} \quad t \leqslant 0$$

In addition, we assume that the system is initially at rest and in equilibrium:

$$x_1(0) = \dot{x}_1(0) = 0 \qquad (3)$$

$$x_2(0) = \dot{x}_2(0) = 0 \qquad (4)$$

The solution of Equations (1) and (2) with initial conditions (3) and (4) may be obtained by classical or

Laplace-Transform methods. We shall treat two separate cases.

For case (a) $F_1(t) \equiv 0$, i.e., the force is applied to m_2 only, and the solution is given by

$$x_1^{(a)}(t) = \frac{F}{k_1}\left(1 + \frac{\omega_1^2 \cos \omega_2 t - \omega_2^2 \cos \omega_1 t}{\omega_2^2 - \omega_1^2}\right) \qquad (5)$$

$$x_2^{(a)}(t) = \frac{F(k_1 + k_2)}{k_1 k_2} \times \qquad (6)$$

$$\left[1 + \frac{\omega_2^2 (\omega_1^2 - \omega_3^2)}{\omega_3^2 (\omega_2^2 - \omega_1^2)} \cos \omega_1 t + \frac{\omega_1^2 (\omega_3^2 - \omega_2^2)}{\omega_3^2 (\omega_2^2 - \omega_1^2)} \cos \omega_2 t\right]$$

For case (b) $F_2(t) \equiv 0$, i.e., the force is applied to m_1 only, and the solution pertaining to this case is

$$x_1^{(b)}(t) = \frac{F}{k_1} \times \qquad (7)$$

$$\left[1 + \frac{\omega_2^2 (\omega_1^2 - \omega_4^2)}{\omega_4^2 (\omega_2^2 - \omega_1^2)} \cos \omega_1 t + \frac{\omega_1^2 (\omega_4^2 - \omega_2^2)}{\omega_4^2 (\omega_2^2 - \omega_1^2)} \cos \omega_2 t\right]$$

$$x_2^{(b)}(t) = \frac{F}{k_1}\left(1 + \frac{\omega_1^2 \cos \omega_2 t - \omega_2^2 \cos \omega_1 t}{\omega_2^2 - \omega_1^2}\right) \qquad (8)$$

where, assuming $\omega_1^2 > \omega_2^2 > 0$

$$2\omega_1^2 = \frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} + \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1 k_2}{m_1 m_2}} \qquad (9a)$$

$$2\omega_2^2 = \frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} - \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1 k_2}{m_1 m_2}} \qquad (9b)$$

$$\omega_3^2 = \frac{k_1 + k_2}{m_1} \qquad (9c)$$

$$\omega_4^2 = \frac{k_2}{m_2} \qquad (9d)$$

and

$$\frac{\omega_2^2}{\omega_1^2} = \frac{1 - Q}{1 + Q} \qquad (9e)$$

where

$$Q = \sqrt{1 - \frac{\frac{4k_1 k_2}{m_1 m_2}}{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2}}$$

It is shown in the Appendix that the roots ω_1 and ω_2 are real, distinct, and positive.

DYNAMIC AMPLIFICATION

We define "dynamic amplification" as the ratio of peak deflection to static deflection.

Case (a):

The static deflection of $x_1^{(a)}$ is $\frac{F}{k_1}$. Therefore, according to the above definition, the dynamic amplification is given by

$$A_1^{(a)} = 1 + \frac{u^2 \cos \omega_1 t - \cos u \omega_1 t}{1 - u^2} \qquad (10)$$

with $u = \frac{\omega_2}{\omega_1}$, where t is chosen such that $A_1^{(a)}$ is a maximum. From Equation (10) we see by inspection that $A_1^{(a)}$ will be a maximum when

$$\left.\begin{aligned} \cos \omega_1 t &= 1 \\ \cos u\omega_1 t &= -1 \end{aligned}\right\} \qquad (11)$$

and therefore

$$\omega_1 t = 2n\pi \qquad n = 1, 2, 3, \ldots$$

$$u\omega_1 t = (2p - 1)\pi \qquad p = 1, 2, 3, \ldots$$

Since the conditions as expressed by Equation (11) must be satisfied simultaneously,

$$0 < u = \frac{2p - 1}{2n} < 1 \qquad (12)$$

and we may conclude that the amplification factor is

$$A_1^{(a)} = \frac{2}{1 - u^2} \qquad (13)$$

where, in order to be admissible, u must be a positive, proper fraction with an odd numerator and an even denominator.

In order to find $A_1^{(a)}$ for arbitrary $0 < u < 1$, we can use the conventional method and require that

$$\frac{dA_1^{(a)}}{dt} = 0,$$

$$\frac{d^2A_1^{(a)}}{dt^2} < 0$$

which results in the following necessary and sufficient condition, respectively, for a maximum of $A_1^{(a)}$

$$\left.\begin{aligned} u \sin \omega_1 t &= \sin u\omega_1 t \\ \cos u\omega_1 t &< \cos \omega_1 t \end{aligned}\right\} \qquad (14)$$

The dynamic amplification factor for $x_2^{(a)}$ is obtained from Equation (6). After some trigonometric manipulation we have

$$A_2^{(a)} = \qquad (15)$$

$$\frac{2}{1 - u^2}\left\{\left[1 - \left(\frac{u}{f}\right)^2\right] \sin^2 \frac{u\omega_1 t}{2} + \left(\frac{u}{f}\right)^2 \left(1 - f^2\right) \sin^2 \frac{\omega_1 t}{2}\right\}$$

where $u = \frac{\omega_2}{\omega_1}$ and $f = \frac{\omega_3}{\omega_1}$, and where t must be chosen such that $A_2^{(a)}$ is a maximum. It is shown in the Appendix that $\left(\frac{u}{f}\right)^2 < 1$ and $f^2 < 1$, and therefore $A_2^{(a)}$ will be a maximum when, simultaneously,

$$\left.\begin{aligned} \sin^2 \frac{u\omega_1 t}{2} &= 1 \\ \sin^2 \frac{\omega_1 t}{2} &= 1 \end{aligned}\right\} \qquad (16)$$

so that

$$u\omega_1 t = (2q - 1)\pi \qquad q = 1, 2, 3,...$$

$$\omega_1 t = (2r - 1)\pi \qquad r = 1, 2, 3,...$$

Conditions expressed by Equations (16) occur simultaneously, and therefore

$$0 < u = \frac{2q - 1}{2r - 1} < 1 \qquad (17)$$

Substituting Equations (16) into Equation (15), we obtain

$$A_2^{(a)} = 2 \qquad (18)$$

for those values of u which satisfy Equation (17).

Case (b):

Because the right hand sides of Equations (5) and (8) are equal, we may conclude that

$$A_2^{(b)} = A_1^{(a)} = \frac{2}{1 - u^2} \qquad (19)$$

by Equation (13) for admissible values of u characterized by Equation (12).

The dynamic amplification of $x_1^{(b)}$ is obtained from Equation (7). After trigonometric manipulation we have have

$$A_1^{(b)} = \qquad (20)$$

$$\frac{2}{1 - u^2}\left\{\left[1 - \left(\frac{u}{g}\right)^2\right] \sin^2 \frac{u\omega_1 t}{2} + \left(\frac{u}{g}\right)^2 \left(1 - g^2\right) \sin^2 \frac{\omega_1 t}{2}\right\}$$

where t must be chosen such that $A_1^{(b)}$ is a maximum and $u = \frac{\omega_2}{\omega_1}$, $g = \frac{\omega_4}{\omega_1}$. It is shown in the Appendix that $g^2 < 1$ and $\left(\frac{u}{g}\right)^2 < 1$. We proceed in a manner similar to to Case (a) and obtain

$$A_1^{(b)} = 2 \qquad (21)$$

which is valid only for values of u which satisfy Equation (17).

DISCUSSION OF RESULTS

Case (a):

The dynamic amplicication of x_1 was found to be

$$A_1^{(a)} = \frac{2}{1 - u^2} \qquad (13)$$

for those values of u which satisfy Equation (12), i.e., in order for Equation (13) to hold, u must be a positive, proper fraction with an odd numerator and an even denominator. For values of u which do not satisfy Equation (12), it is necessary to use Equations (14), thus requiring the solution of a transcendental equation.

It should be noted that Equation (13) provides us with an upper bound for the amplicication factor of $x_1^{(a)}$, as is readily seen by inspection of Equation (5). Table 1 shows a series of values of the amplification factor for "inadmissible" values of u ,and provides a comparison with values calculated with the formula, equation (13). It is seen that the use of the formula, even though not strictly applicable for these values of u, results in factors which are somewhat larger than the exact value. Thus the formula provides us with "conservative" values from the point of view of stress analysis, for arbitrary frequency ratios $0 < u < 1$.

The dynamic amplification for $x_2^{(a)}$ is two (2) provided u satisfies Equation (17). The factor 2 represents an upper bound, non-admissible values of u giving rise to a somewhat smaller factor.

A graphical picture of these results is given in Figure 2, which, it is hoped, will prove useful in applications.

TABLE I

u	$A_1^{(a)}$ or $A_2^{(b)}$		
	Exact	Approximate	% Error
0.2	2.00	2.04	2.00
0.4	2.27	2.38	4.85
0.6	2.97	3.13	5.40
0.8	5.30	5.56	4.90

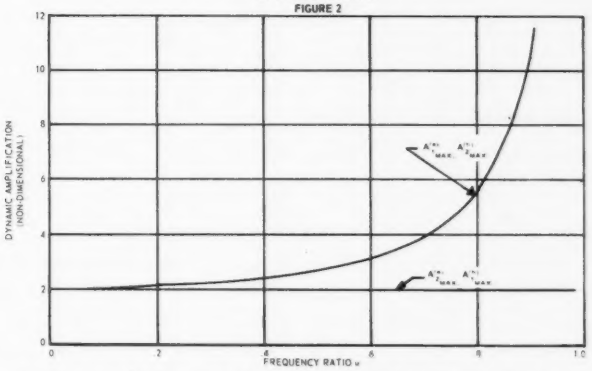
Case (b):

An upper bound of the amplification factor for $x_1^{(b)}$ is two (2), and for $x_2^{(b)}$ it is (see Equation 19)

$$A_2^{(b)} = \frac{2}{1 - u^2}$$

The arguments are similar to Case (a), and the results are shown graphically in Figure 2.

DYNAMIC AMPLIFICATION AS A FUNCTION OF FREQUENCY RATIO
FIGURE 2



It should be noted that the graph, Figure 2, is an exact plot of the dynamic amplification factor if u satisfies Equation (12) for $A_1^{(a)}$ and $A_2^{(b)}$, and Equation (17) for $A_1^{(b)}$ and $A_2^{(a)}$. The graph is approximate and provides an upper bound for all other cases.

In general, the analysis of a physical system requires some form of idealization, i.e., a mathematical model is developed by lumping the structure into discrete masses and springs. This lumped system is then subjected to mathematical analysis. We have shown that the results of such an analysis depend markedly upon the nature of the lumping process. For the step loading considered in this investigation, the load factor for one of the masses of the two-degree-of-freedom system is always larger than two, whereas for a single-degree-of-freedom system subjected to the same disturbance, it is always less than or at most equal to two.

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APPENDIX

In order that the roots ω_1 and ω_2 as expressed by Equations (9a) and (9b), be real,

$$\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1 m_2} > 0 \qquad (22)$$

or, upon rearranging,

$$\left(\frac{k_1}{m_1} - \frac{k_2}{m_2}\right)^2 + \frac{k_2}{m_1}\left[2\left(\frac{k_1}{m_1} + \frac{k_2}{m_2}\right) + \frac{k_2}{m_1}\right] > 0 \qquad (23)$$

Since all masses and springs are characterized by positive constants, the above inequality is satisfied, and it is thereby proved that the roots are real.

To prove that the roots are positive we must show (see Equation 9b) that

$$\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} > \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2}} \qquad (24)$$

Since both sides of this inequality are positive, we may square both sides:

$$\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 > \left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2} \qquad (25)$$

This inequality is clearly satisfied in view of the fact that all constants are positive. Therefore both roots are positive. Since the radicand in Equations (9a) and (9b) is never zero (Equation 22), the roots are distinct. From the above results it immediately follows (by inspection of Equations 9a and 9b) that

$$0 < u = \frac{\omega_2}{\omega_1} < 1 \qquad (26)$$

We shall now prove that $\left(\frac{u}{f}\right)^2 < 1$, where $u = \frac{\omega_2}{\omega_1}$, and $f = \frac{\omega_3}{\omega_1}$. This is equivalent to proving that $2\omega_2^2 < 2\omega_3^2$. From Equations (9b) and (9c) we have

$$\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} - \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2}} < \frac{2(k_1 + k_2)}{m_1} \qquad (27)$$

or, rearranging

$$\sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2}} > \frac{k_2}{m_2} - \frac{k_1 + k_2}{m_1} \qquad (28)$$

If we combine Inequalities (24) and (28), and eliminate the radical we obtain

$$\frac{2(k_1 + k_2)}{m_1} > 0 \qquad (29)$$

which is certainly true. Because of the preceding, and in view of Inequality (24) we may state that

$$0 < \left(\frac{u}{f}\right)^2 < 1 \qquad (30)$$

To prove that $\left(\frac{u}{g}\right)^2 < 1$, where $u = \frac{\omega_2}{\omega_1}$ and $g = \frac{\omega_4}{\omega_1}$, is equivalent to proving that $2\omega_2^2 < 2\omega_4^2$. Hence we must show that (see Equations 9b and 9d)

$$\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2} - \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2}} < \frac{2k_2}{m_2} \qquad (31)$$

or, rearranging,

$$\frac{k_1 + k_2}{m_1} - \frac{k_2}{m_2} < \sqrt{\left(\frac{k_1 + k_2}{m_1} + \frac{k_2}{m_2}\right)^2 - \frac{4k_1k_2}{m_1m_2}} \qquad (32)$$

If we combine Inequalities (24) and (32), eliminate the radical, and simplify, we obtain

$$\frac{k_2}{m_2} > -\frac{k_2}{m_2}$$

or

$$1 > -1$$

Because of the above, and in view of Inequality (24),

$$0 < \left(\frac{u}{g}\right)^2 < 1 \qquad (33)$$

RELIABILITY PLANNING IN SPACE SYSTEMS

BY VERNON L. GROSE
LITTON INDUSTRIES

ABSTRACT

It is recognized today that the reliability of space vehicles and systems must far exceed the presently achieved levels of reliability before man can venture into outer space confident of his safe return to earth. Having exhaustively surveyed the statistical techniques of prediction and their effect in achieving reliability, it is proposed that none of these techniques have proved sufficiently effective to warrant their employment in future systems. A method is proposed which utilizes design analysis techniques rather than mathematical models to establish design goals.

INTRODUCTION

It is evident to persons concerned with reliability problems that there is no magic panacea or "plug-in" formula that will solve these problems. Although the use of "Dynamic Decimals" and other numerical expressions have been increasingly employed in recent years to predict future performance, it has become apparent to both the creator and the recipient of these numbers that, more often than not, the contractor's prediction is simply juggled until it matches the customer's requirement.

Disenchantment with numbers, however, need not deter one from the scientific pursuit of reliability achievement. Now that man is poised on the threshold of exploring and inhabiting outer space, it is unlikely that he will be successful until space vehicles become more than exotic playthings. In fact, the advent of *manned* space exploration spurs the scientist and engineer to avoid the superficiality of designing only to pass a qualification test or to meet minimal performance criteria. It becomes immediately manifest, now that human life is at stake, that the amethodical approach is untenable.

If a method is required, then what must the method supply? It must provide scientific and financial direction for the proper allocation of manpower and priority of effort. Further, the cooperation of designers is mandatory. The method herein has been successfully utilized at the conceptual or preliminary design stage.

REVIEW OF RELIABILITY PREDICTION

In the past eight to ten years, the art-science of reliability has been predominately occupied with quantitative prediction. The military customer, because of the increased cost of weapon systems and a constantly reducing inventory of any particular system, had initially presented a *logistical* problem to its contractors. It was imperative that a very high probability of successful operation exist for each and every system if the defense budget was to remain economically feasible for the American people. With an intense desire to quantify this need to the contractor and because the word "probability" appeared, statistical mathematicians were consulted.

In this near-decade, the types of equipment being statistically analyzed have changed. Ten years ago, the manned aircraft was the predominant weapon system, and the pilot could always be relied upon to not only report airborne malfunctions but also bring the aircraft back to the base in spite of failures. A few years later, the guided missile appeared on the scene, and to many persons, this was no more than a very expensive firecracker. Because there were no human beings aboard, the malfunctions, however spectacular, could be excuse by such statements as: "We really do not learn anything from these firings unless we experience a failure."

Ironically, we are about to return to a manned system--the space ship. The step into space is a geometric rather than arithmetic advance, and although we are again to man our gadgetry, it is highly probable that instead of man being an asset in overcoming unreliability, he may well become a detriment, even though his life will be worth just as much to his loved ones as it was in the manned aircraft! It is pertinent, then, that the prediction techniques utilized in manned aircraft and guided missiles be reviewed from two viewpoints: (1) whether the techniques accomplished their intended purpose in manned aircraft and guided missiles; and (2) whether, providing the techniques were successful, they appear to have promise for space systems.

ACHIEVEMENT TO DATE

In speaking of achievement, it is important to define what is to be achieved. *Reliability* is to be achieved--not *prediction*. Therefore, if prediction techniques were to be refined and perfected to the point where prediction were 100 percent accurate, there would still be no guarantee as to whether the reliability required would be achieved. This is particularly true because the prediction experts and the designers are two autonomous groups who, in general, work entirely independently of one another. To the extent that these two groups can communicate and actually experience empathy, reliability achieve-

ment and prediction accuracy will possess correlation. To re-phrase the premise of evaluation, achievement of reliability prediction must be measured in terms of impact on the engineering designer so that he designs reliably. The achievement of reliability in the following areas should be considered as due primarily to the techniques of statistical prediction:

(1) There has arisen in industry a definite awareness or consciousness of the need to achieve reliability, and this consciousness has certainly been focused through such simple statistical tools as the familiar product rule until reliability has actually been achieved. While it is probably generous to attribute all the consciousness of unreliability to the impetus of numbers, mathematical prediction has played a major role.

(2) An awareness of the effects of variability in performance parameters has become increasingly evident in engineering thinking, and this awareness not only has helped achieve reliability but is to be credited to the mathematical statistician because the majority of engineers have never studied statistics formally.

(3) A number of quantitative indices for expressing failure; e.g. percent of total parts failing per 1000 hours of operation, have been introduced by the statistician as a means of correlation of data, and this has probably aided indirectly the achievement of reliability.

These three products of reliability prediction by statisticians have effectively impressed the engineering designer, and it can be said that reliability has been achieved thereby.

INEFFICACY TO DATE

Statistical prediction techniques have failed to contribute to reliability achievement in a number of areas and for a number of reasons. There are undoubtedly many facets to the impotence of prediction, and the subtle shift in application of prediction from logistics to design goals could well be the crucial one. In retrospect, it appears likely that those responsible for statistical design goals either (1) were given assumptions by engineering personnel which were incomplete, (2) assumed (on their own behalf and in engineering ignorance) incomplete parameters, or (3) deliberately oversimplified a problem which they recognized as complex. Deviating, then, from a strictly logistical consideration which would have permitted the customer in the most pessimistic instances to cancel projects prior to development, the statisticians confronted the engineer with mathematical design goals which were sufficiently ambiguous as to leave him effectively untouched by their significance. Thus, it is highly unlikely that any customer has cancelled or ever will cancel a contract strictly on the strength of a predicted reliability number.

The inability of prediction techniques to influence reliability achievement is felt to be sufficiently complex in attribution that both the overt and covert aspects, from the viewpoint of the reliability practitioner, are discussed.

THE OBVIOUS ASPECTS OF INEFFICACY

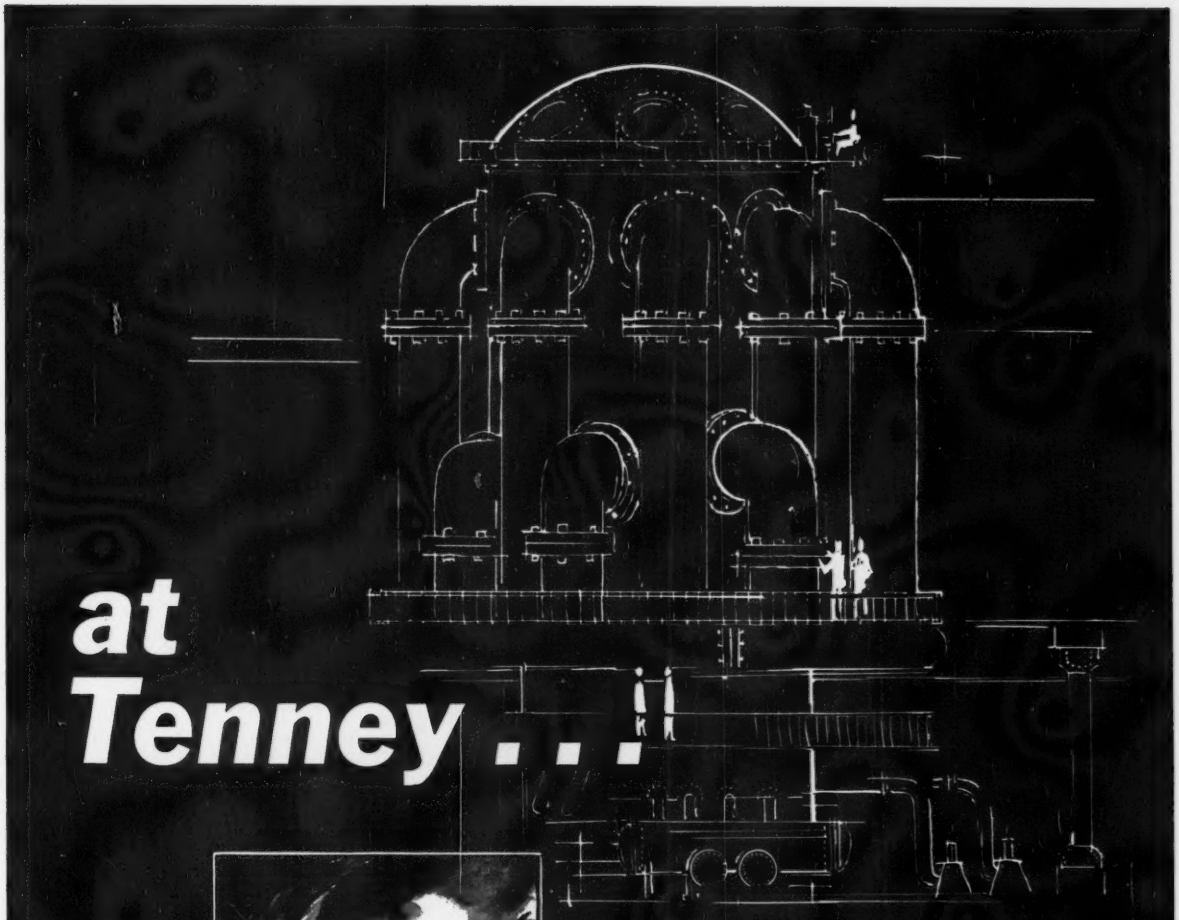
A recent book, in a chapter entitled *Scientism*, discusses a prevalent philosophy which seeks to define mathematically the diverse complexities of human behaviorism even to the extent of ultimately "scientifically" determining ethics![11] The same confusion which exists in the minds of these so-called social "scientists" between science and scientism likewise exists in the thinking of a majority of those persons involved in reliability prediction. Just because a person desires, for convenience sake, some numerical representation of a complex situation is no reason to believe that such a number actually exists.

Reliability has been generally defined as consisting of four parts: (1) Probability, (2) Performance, (3) Environment, and (4) Time. One of the obvious reasons that statistical statements about reliability have proved inefficacious is that the military customer often leaves nothing to be solved as he specifies all four parts. As a suggestion to those who specify reliability, one of the four constituent parts should be treated as a variable because if this is not done, the contractor is forced into a yes-or-no situation, and this invariable leads to the "we-need-this-contract" type of optimism. There is recognition of this danger by some of the military services, and instead of speaking of discrete goals, they advocate a *range* of values for reliability.[6]

Those persons desirous of utilizing statistics as a design tool may have originally entertained hope of influencing designers, but the approach of numerical goals proved illogical to a designer, (e.g., how was he to design differently for 0.97031 reliability as contrasted to 0.99864 reliability?), that it met with almost immediate rejection. The schism resulting from this rejection has not been bridged to the extent that the prediction expert is able to tell a specific design group with reasonable confidence that their designs are the weakest in the system and must be improved. While the prediction personnel blame the schism on the lack of understanding of statistics by engineers, it is more likely that an invalid premise rather than a breakdown in communication is the culprit.

One of the difficulties encountered in predicting system reliability is that the methods available generally treat the *theoretical* reliability; i.e., that reliability which is inherent in the design but not yet "practicalized" by production techniques, procurement, inspection, shipment to the field, and maintenance by the customer. These variabilities, as a general rule, are not only difficult to predict but also of great influence on over-all reliability. Prediction must be based on prior experience or knowledge. Whenever the amount of conjecture becomes appreciable with respect to knowledgeable inputs, the prediction is in jeopardy. One of the most obvious shortcomings of reliability prediction is that it has consisted of compounded conjecture with too little actual data. It would appear that time-effort-money would be better utilized if spent on gathering data (testing) rather than on arranging

Continued on page 23



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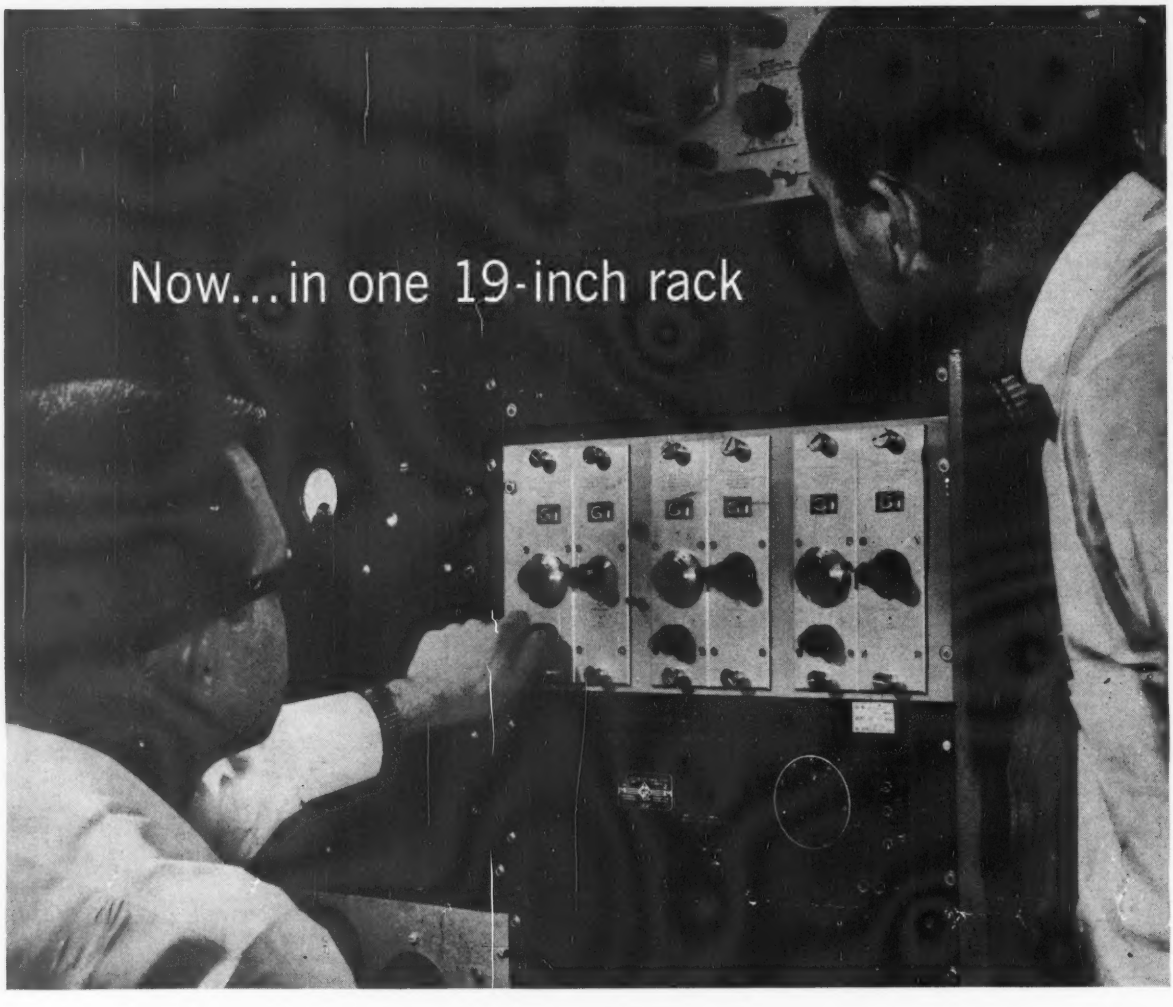

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DESIGN for MANNED REENTRY GLIDE

Raymond J. Comenzo and Lawrence D. Wing Advanced Programs Group, The Martin Company

ABSTRACT

The thermal environment resulting from aerodynamic heating during reentry is the most critical factor in the design of a glide reentry vehicle. Simple methods are available for estimating the intensity of the heat flux on blunt noses, wing leading edges and wing lower surfaces. These methods involve the use of only the simplest of aerodynamic parameters and are valid through the range of significant heating.

Some form of thermal protection of the vehicle components and crew must be provided. The air-conditioning systems described have adequate capability and reliability to maintain the manned reentry cabin at a safe and comfortable temperature.

INTRODUCTION

One of the most challenging and difficult problems associated with manned space flight is the design of a reentry vehicle capable of safely delivering a delicate human cargo, traveling at extremely high velocities, from the fringes of the atmosphere to the earth's surface. Vehicle performance must be both controllable and predictable. If controllability is lacking during reentry, there may be a buildup of accelerations beyond human tolerance. Unless the flight path can be predicted accurately, a preselected landing area must be ruled out and it may be impossible to locate the vehicle after landing.

The initial steps leading to the successful recovery of man from space were taken in the X-1 and X-2 experimental programs. These early efforts led to the present X-15 experimental rocket airplane which, in turn, may be considered a stepping stone to the imminent Mercury and Dyna-Soar programs. Mercury and Dyna-Soar are two of the most promising approaches to manned reentry: ballistic and winged glide vehicles.

The ballistic body concept has the advantage of greater simplicity, but its disadvantages include marginal controllability and maneuverability for making corrections in the reentry flight path to prevent excessive aerodynamic heating or accelerations, even though the flight path angle is appreciably in error at initiation of reentry. The virtual lack of maneuverability also greatly reduces the ballistic vehicle's capability of navigating to a preselected landing area.

Consequently, design problems of a winged reentry glide vehicle are the deliberate subject of the present article.

One of the purposes of glide reentry is to minimize extremes of environment such as temperature and acceleration, and to minimize the rate of change of these and other parameters. It may be necessary, on the other hand, to consider the differences in atmospheric parameters between day and night and between different climates.

In evaluating the reentry environment in context with the requirements of preliminary design, environmental parameters such as temperature, acceleration and air density must be analyzed in relation both to vehicle design parameters and to human factors. For vehicles of various wing loadings, tolerance requirements for width of flight corridor must be examined--particularly in relation to deviations from standard atmosphere.

Variation of air-conditioning system weight with respect to flight time is another important criterion. Here we shall consider two cockpit cooling systems: one based on the use of liquid air and the other on the use of boiling water. In addition, it will be pertinent to define methods of estimating aerodynamic heat inputs to blunt noses, wing leading edges and wing lower surfaces.

ENVIRONMENT

In predicting the environment which a glide reentry vehicle will encounter, certain assumptions must be made which are subject to significant variations. It is necessary, therefore, to examine the effects of these variations. The extreme velocities of the reentry vehicle result in flight over a large portion of the earth in a relatively short time. Both day and night conditions and changes of climate will be encountered. Thus, any assumptions of a constant, predictable atmosphere are invalid.

Both the acceleration and the intensity of aerodynamic heating are sensitive to the vehicle velocity and air density. It would be relatively simple to predict a safe reentry corridor on a velocity-altitude plot (e.g., Fig. 1) if the atmospheric density were a function only of altitude. But the problem is complicated by the introduction of variations of density with altitude, climate, time of day (position of vehicle relative to sun and earth) and even season of the year.

Figure 1 shows the effect on a line of constant stagnation point temperature (a barometer for the general heating environment) drawn on an altitude versus velocity curve of a variation in density of 50% from the ICAO extended model atmosphere values.

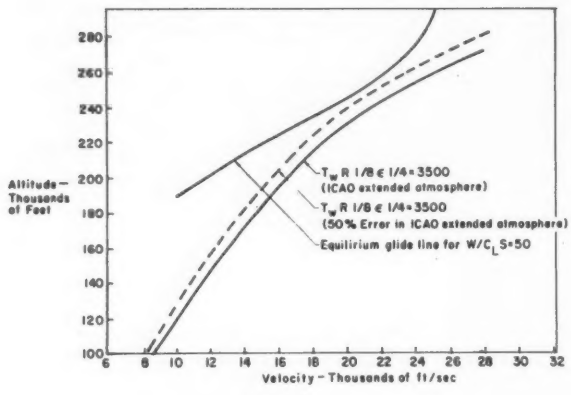
Altitude – Thousands of Feet
Velocity – Thousands of ft/sec
T_w R 1/8 ∈ 1/4=3500 (ICAO extended atmosphere)
T_w R 1/8 ∈ 1/4=3500 (50% Error in ICAO extended atmosphere)
Equilirium glide line for $W/C_L S=50$

Fig. 1.
Effect on Flight Corridor of Variation of Density from Standard

If the design temperature limit of a particular vehicle were defined as the temperature which corresponds to a stagnation point temperature parameter of 3500, the vehicle would have the temperature capability of flying anywhere above the lower solid curve of Fig. 1--the upper limit being defined by the aerodynamic capability of the wings to sustain an equilibrium glide. If, on the other hand, the assumed density at the appropriate altitude were in error by 50%, the temperature limit line of Fig. 1 would be represented by the dotted line--designated "50% error in ICAO atmosphere density."

Clearly, the lower limit of the allowable flight corridor has been significantly increased and flight in the region between the two "3500" lines would result in critical damage to the vehcile.

ESTIMATING SURFACE TEMPERATURES

Ablative techniques for handling reentry heating result in an unpredictable decay of the aerodynamic characteristics of the vehicle. Also, no practicable materials are now known which ablate with good thermal efficiency at the relatively low heat transfer rates associated with the acceleration restrictions on a manned reentry vehicle. For this reason, radiation is the basic technique for handling the heat developed during the reentry glide. This technique may be supplemented by either a structural cooling system or insulation--or by both.

Two methods of predicting the temperature at which the vehicle skin would radiate away *all* of the heat transferred to it from the boundary layer (equilibrium wall temperature) are considered here. The first is used to estimate temperatures over the lower surface of the wings and the second to obtain temperatures on the blunt nose and wing leading edges (Fig. 2).

It can be shown that the maximum skin temperature of the insulated lower surface of a wing is a function of W/SX only, where W = weight of vehicle, S = wing area

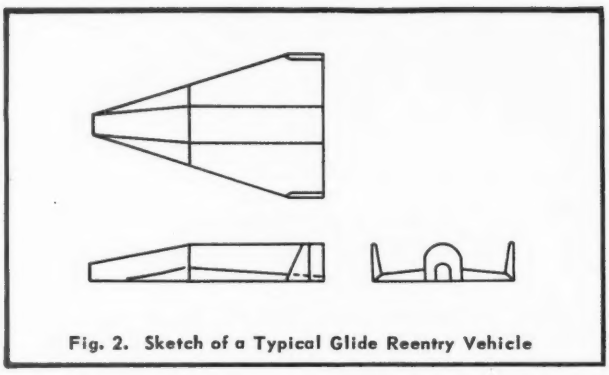

Fig. 2. Sketch of a Typical Glide Reentry Vehicle

and X = distance from leading edge. Moreover, $T_{max} = 1810 \left(\frac{W}{SX}\right)^{0.1205}$ (°R). The derivation of this equation appears in the Addendum. Since the wall temperature is proportional to the fourth root of the heat flux, it does not vary excessively with flight velocity. The variation may be shown to be

$$T = V^{0.602} \left(1 - \frac{V^2}{V_c^2}\right)^{0.1205} \qquad (1)$$

where
V = vehicle velocity
V_c = the circular orbit velocity of the vehicle at the appropriate altitude.

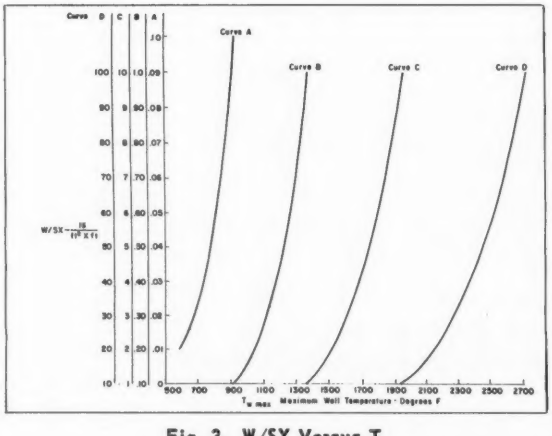

Fig. 3. W/SX Versus T_{max}

Figure 3 shows the variation of T_{max} with the vehicle parameter, W/SX. For a wing loading (W/S) of 30 psf and a distance from the leading edge (X) of 2 feet,

the parameter W/SX is 15. This, from Fig. 3, yields a maximum temperature $T_{w_{max}}$ = 2050° F. Figure 4 is used in conjunction with Fig. 3 to estimate the temperature of the point of interest at some velocity other than 22,000 fps (at which $T_{w_{max}}$ occurs). Note that this ratio is independent of the value of W/SX.

Continuing the above example, the equilibrium skin temperature two feet aft of the leading edge and at a time in the reentry trajectory when the velocity has decreased to 16,000 fps is found by multiplying $T_{w_{max}}$ (2050° F) by the factor from Fig. 4 at 16,000 fps (0.914). Thus, T_w (at V = 16,000 fps = 0.914 x 2050 = 1874° F.

It must be emphasized that Figs. 3 and 4 assume that the glide vehicle is entering the atmosphere in equilibrium glide (aerodynamic lift plus centrifugal force = vehicle weight). These curves have been found to be accurate within about 3% compared to several more compared to several more complicated methods of calculation.

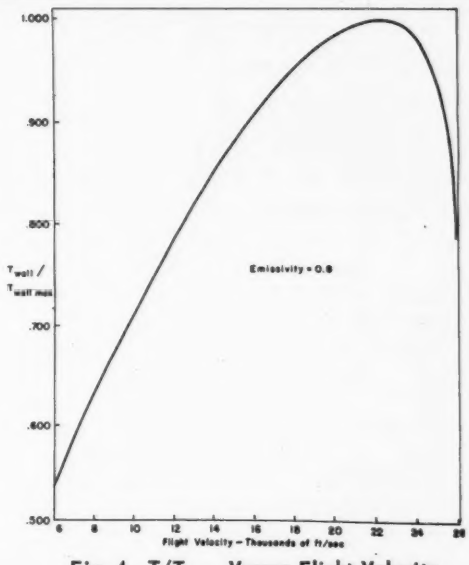

Fig. 4. T/T_{max} Versus Flight Velocity

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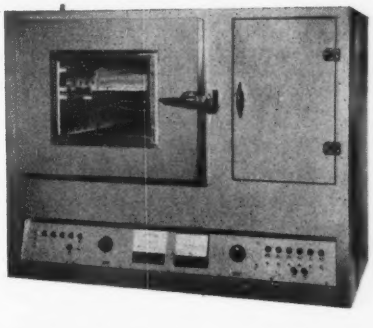

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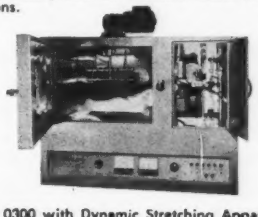

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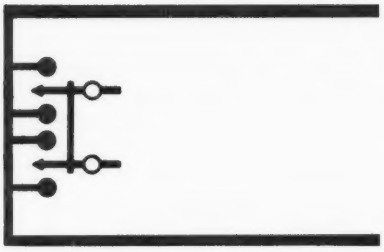

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Designing an Effective Test Plan for Reliability Evaluation by W.L. MOTSCH & R.G. DEMPSEY; Santa Monica Division, Douglas Aircraft Company. The principles to be followed in the formulation of a missile component test plan to furnish information for reliability evaluations, will be presented. The advantages and disadvantages of such techniques as life testing, designed experiments, and other possibilities will be discussed.

Integrated Test Plans by R.H. HOVER; Missile Division, North American Aviation, Inc. The integrated test plan uses factorial experiments at component level and in addition, regression experiments at level for a complete missile program. The tests are non-destructive, and will allow for early correction of defects.

A Combined Environmental Testing Program for Increasing Atlas Missile Reliability by C.C. CAMPBELL; Convair Astronautics Division, General Dynamics Corp. The Atlas reliability test program is based on the concept of early detection of component weaknesses in design, materials, and fabricating techniques so that corrective action can be implemented before operational failures occur. An explanation of the techniques devised for determining various weaknesses and photographs illustrating failed specimens, with corrective action are included.

Environmental Specifications for the 'Able' Series of Space Vehicles by S.C. Morrison; Space Technology Laboratories, Inc. The derivation and content of environmental test specifications for lunar probes, satellites and space probes are discussed. Also included will be the difficulties encountered in attempting to define some of the environments, and final production environmental test specifications.

Nuclear Rocket Environment by H.A. FLAGG, G. MANDELL AND L.E. WHITE, Aerojet-General Division, General Tire and Rubber Company. A nuclear rocket system is considered in which the energy is added to the working fluid with an unshielded, gas-cooled reactor. The nuclear rocket environment is described by treating the superposition of reactor conditions upon the cryogenic and light-weight conditions.

Space Radiation as an Environmental Constituent by R.R. BADERTSCHER & R.E. HESS, Battelle Memorial Institute. Available data treating the composition. flux values, and energy spectra for Van Allen-type and true cosmic radiation are reviewed. Considering the interaction of these types of radiation, a qualitative description of the secondary radiation field is suggested from the general theory related to primary radiation. Response of typical materials to this radiation is examined.

Radiation Shielding Problems in a Manned Space Flight by L.E. WALLNER & H.R. KAUFMAN, NASA Lewis Research Center, Cleveland. The space astronaut will be faced with serious radiation hazards on a long journey into outer space. This paper describes some of the payload limitation problems arising from two radiation sources: cosmic radiation, and that resulting from a nuclear powerplant.

LIFE SCIENCES FOR SPACE USES CHART

The extent of knowledge in the Life Sciences required for manned space flight has been compiled for the first time by The Garrett Corporation's AiResearch Manufacturing Company of Los Angeles.

The information, compiled in chart form, was prepared by Frederick H. Green, assistant chief of preliminary design, AiResearch Manufacturing Company of Los Angeles; James N. Waggoner, M. D., medical director, AiResearch; and Albert A. Schwichtenberg, M. D., chief, department of aerospace medicine, Lovelace Foundation, Albuquerque.

The chart generally deals with stresses on man's environment, psychological, physiological, chemical, physical and mechanical make-up when he travels into space.

Continued on page 20

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A new Hot-Cold-Humidity Chamber using liquid CO_2 for cooling has been introduced by DEVELOPMENT ENGINEERING CO., INC. The chamber features the DEVELCO–PULSE Control System which gives accuracy of control in both the heating and cooling cycles, economy of operation in the use of liquid CO_2 and controlled rates of heating and cooling for cycling the test chamber. The chamber drops to minus 100°F. in a few minutes. It has an accuracy of control of better than ± 1°F.

depending upon instrumentation. Construction features are a stainless steel interior, externally mounted motor and 5" insulation.

Illustrated is a Model C8 CO_2 front opening chamber, on a stand, with dry bulb-wet bulb program controller-recorder mounted in conjunction with the DEVELCO Control Unit. Units are available from table top lab size models to walk-in rooms.

DEVELOPMENT ENGINEERING CO., INC. 9 Cross Street Norwalk, Connecticut.

NEW LOW–COST, PROTABLE VIBRATION TESTER FOR QUALITY CONTROL

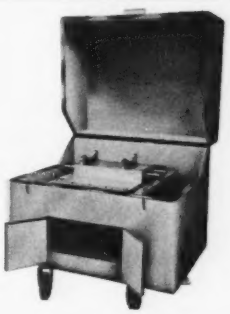
A new simplified portable vibration tester for quality control analysis which can be operated by factory personnel is being marketed by Rototest Laboratories, Lynwood, California.

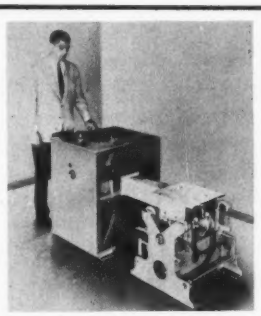
The new tester, called Rotocon,* was developed to provide an easy to operate tool for exposing assembly defects or substandard parts of missile-borne electrical and electronic components and equipment.

In addition to its portability and low initial cost, other features of Rotocon* are: low operating and maintenance, excellent sound proofing, and simple data take-off. In operation there is less than 75 db of noise measured six feet away from the machine. The tester provides a fundamental output vibration at 50 cps and overtones at predetermined multiples. The only operations required to test a component are to bolt component and its fixture to table of the machine and turn on switch. A timer automatically turns machine off after appropriate length of time.

For more information write: Rototest Laboratories, Inc., 2803 Los Flores, Lynwood, California.

*Rotocon is a trademark of Rototest Laboratories, Inc.





NEW ENVIRONMENTAL VIBRATION MACHINE FOR TESTING ELECTRONIC COMPONENTS AND ASSEMBLIES

A new reaction-type environmental vibration machine, designed especially for testing small electronic components and assemblies in accordance with procedures described in MIL–T–19500B, has been introduced by the L. A. B. Corporation of Skaneateles, New York. Designated the RV–15–25, this vibration machine is capable of producing accelerations up to 25 G's continuous at nominal load. The machine is also suited to general testing applications where a wide frequency range, larger excursion, higher accelerations and continuous operation are required.

The machine has a maximum load capacity of 50 pounds, nominal load of 30 pounds and a table mounting surface of 15" x 15". Maximum excursion is .375" at nominal load and is adjustable from 0 to maximum at standstill. Frequency range is adjustable from 10 to 100 CPS. Cycling period is adjustable from 1.5 to 60 minutes per cycle in stepless intervals. Frequency range for cycling may be selected between any two points on the frequency scale.

For complete information and price, write L. A. B. Corporation, 700 Onondaga Street, Skaneateles, New York.

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leader in solving unique test problems

Continued from page 18

NEW PROCEEDINGS Available at Conference

The National Electronics Conference announces that hard-bound editions of its 1960 PROCEEDINGS will be available during registration for the 16th Annual Meeting and Exhibition.

The NEC believes lecture sessions will be more profitable if listeners can follow the lectures in printed form, or review the paper afterward. Price per copy is five dollars at the registration desk, six dollars for mail orders.

The PROCEEDINGS contains 100 papers which will be presented during the meeting, October 10–12, in Chicago's Hotel Sherman. Subjects include all phases of data gathering and transmission, computers, circuit and control theory, parametric devices, microelectronics, plasma physics, and engineering management, plus a special joint NEC-AIEE symposium on logic and switching circuits.

NEW ATMOSPHERE TABLE ON PLASTIC RULER FROM TENNEY ENGINEERING, INC.

Tenney Engineering, Inc., of Union, N.J., manufacturer of environmental equipment, has a six-inch plastic ruler for engineers showing the new 1959 ARDC model atmosphere table with pressures and temperatures encountered at various altitudes up to two million feet.

It shows temperatures in Fahrenheit, and air pressure in mms and inches of Hg and also psia for altitudes from sea level to the 2 million mark. Three temperature inversions, at 90,000, 180,000 and 325,000 feet can be clearly followed in hundredths of degrees, along with the interesting plateaus between 37,500 and 80,000 feet and between 250,000 and 300,000 feet.

PROCEEDINGS OF 1959 NATIONAL ELECTRONICS CONFERENCE AVAILABLE

PROCEEDINGS of the National Electronics Conference 1959 (Volume 15) are now available. This book contains all of the technical papers and addresses presented at the 1959 Conference. The 109 technical paers cover electronic research, development and application of antennas, circuits, communications, computers, electron tubes, engineering management, instrumentation, magnetic amplifiers, materials and communication, microwave, radar, servomechanisms, solid state devices, parametric amplifiers, and engineering writing and speech.

Volume 15, NEC PROCEEDINGS, contains 1089 pages, cloth bound. Copies may be purchased at $10.00 each from National Electronics Conference, Inc., Room 2104, 228 North La Salle Street, Chicago 1, Illinois.

CORRECTION

In the June issue of the Journal, the article "A Synopsis of Natural Environments to Heights of 1,000 Km", contained an error. Both Authors have been kind enough to point out that on page 6, section B.1. the pressure would be 8,000 psi at a depth of 18,000 ft., however the sentence should be changed as follows:

"of importance is the maximum depth which exceeds 30,000 feet with a corresponding pressure of approximately 13,300 pounds per square inch."

CALL FOR PAPERS

1961 IES National Meeting

The Institute of Environmental Sciences is planning a three-day technical meeting on 5, 6, and 7 April 1961, at the Sheraton-Park Hotel in Washington, D. C. This meeting will be devoted to problems related to Measurement and Simulation of the Environment. The meeting will be divided into three concurrent sessions dealing with (1) Ground Environments, (2) Marine or Sea-bourne Environments, and (3) Aerospace Environments. Associated with the technical sessions there will be a large trade and product exhibition at the hotel devoted to the same theme. The purpose of the meeting is to disseminate the latest available information in this rapidly growing field of science in order to accelerate progress in the development of reliable military equipment by offering a comprehensive interchange of information in this critical reliability area, the environments.

Deadline for abstracts is 30 Nov. 60. Deadline for completed papers is 30 Jan. 61.

All communications should be addressed to: Mr. David Askin, Chief, Test and Evaluation Br., 1730/230; U.S. Army Ord. Arsenal, Frankford; Phila. 37, Penna. (Telephone JE5–2900, Ext. 6147), or Mr. Raymond G. Yeager; Chrysler Corp., Missile Div., P.O. Box 2628, Detroit, 31, Mich.

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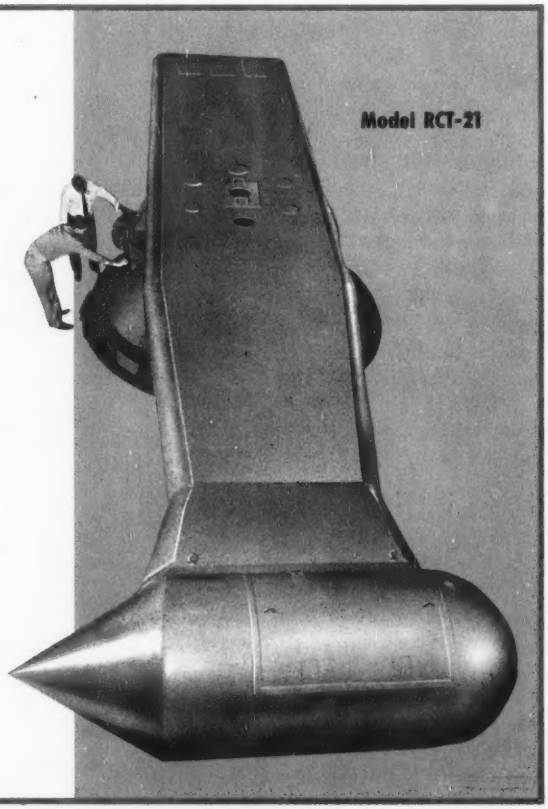

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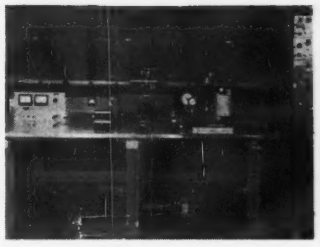
Continued from page 10

and rearranging numbers.

Random sampling simulation, sometimes known as the Monte Carlo method, has even been advocated for reliability prediction because other mathematical models appear unable to cope simultaneously with the effects on system output of all the known environmental stresses, operational stresses, time-dependent deterministic and stochastic events, and randomly occurring castastrophic events such as part wearout. Even though the random sampling method is uniquely able to integrate these separate effects, advocates of its use point out that it is more time-consuming and probably more costly than the use of other predictive models.[4]

The more accurate the predictive technique used, the more sensitive it is to a specific deviation from initial inputs. In fact, caution on the part of some statisticians regarding some of the more popular statistical statements has caused "robustness" studies to be undertaken on techniques which are based on an underlying exponential life distribution -- "robustness" being defined as the ability of a statistical test to retain its validity even though certain assumptions under which the test was conducted may not be true.[9] So, since the design is seldom stable more than a day or two throughout its developmental life, the only true statement that can be made for a developmental prediction is that it is an estimate of the design reliability as it was on a particular day, and the designer has a stock answer for any weakness supposedly revealed by the prediction; i.e., that he has long since corrected the items shown to be deficient in the estimate. This puts the predictor in the position of chasing the pot of gold at the end of a rainbow.

To be continued in the December Issue



CERTIFIED ENVIRONMENTAL TESTING

environmental test report | NO. 60-2

PROBLEM:

Life cycle testing of a Mach Computer. Tests required cycling and modulating of static and differential pressure inputs, with outputs read as a function of Mach. System was to be subjected to 10,000 pressure cycles (at rate of 20 per hour), plus superimposed pressure modulating cycles and electrical operation.

SOLUTION:

Special set-up shown above was designed for this test. A manostat and two solenoid valves were provided for each of the two pressure cycles. The two systems were individually geared to a single variable-speed drive and programming system. Modulating pressures were provided by two motor-driven bellows. Outputs were observed on a recorder.

Complete file of Environmental Test Reports will be sent on request

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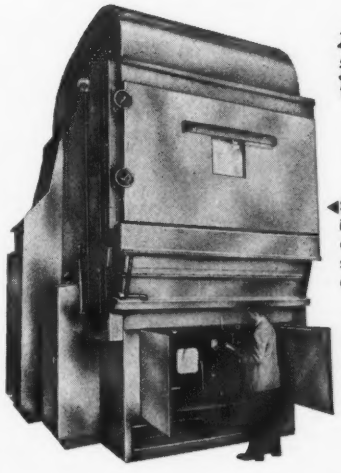

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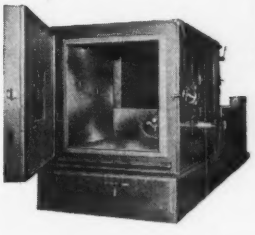
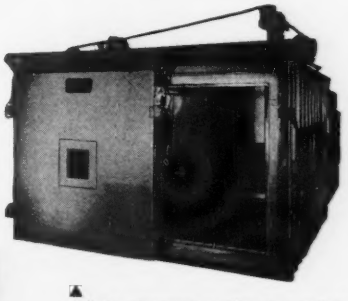


◀Sand and dust chamber includes automatic dust density control and streamlined air-flow design.



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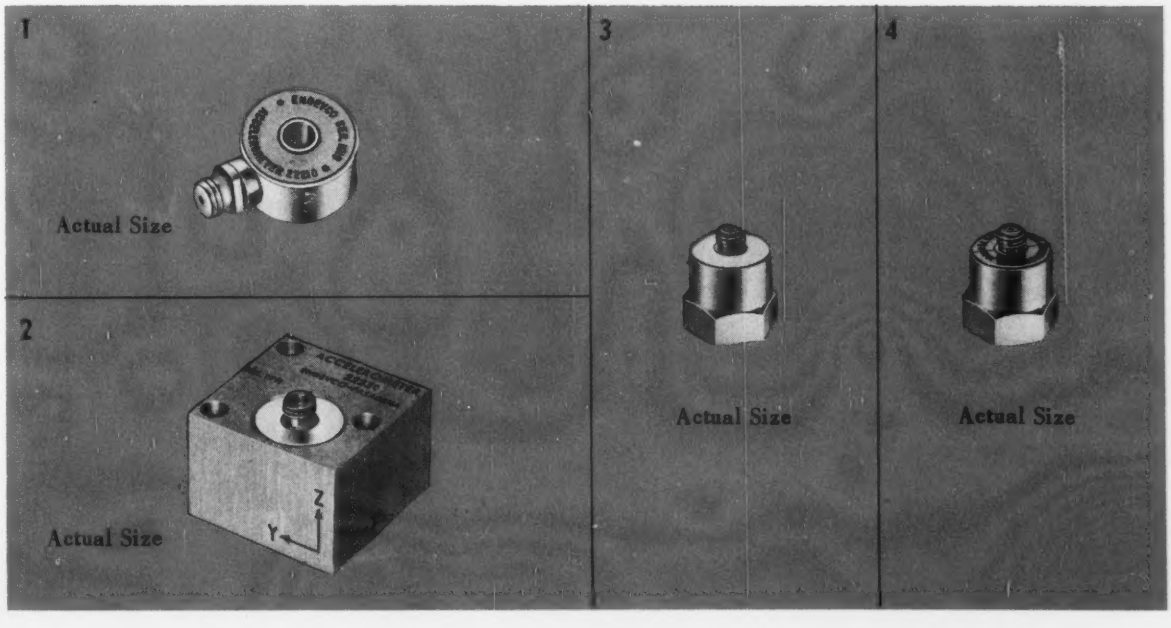

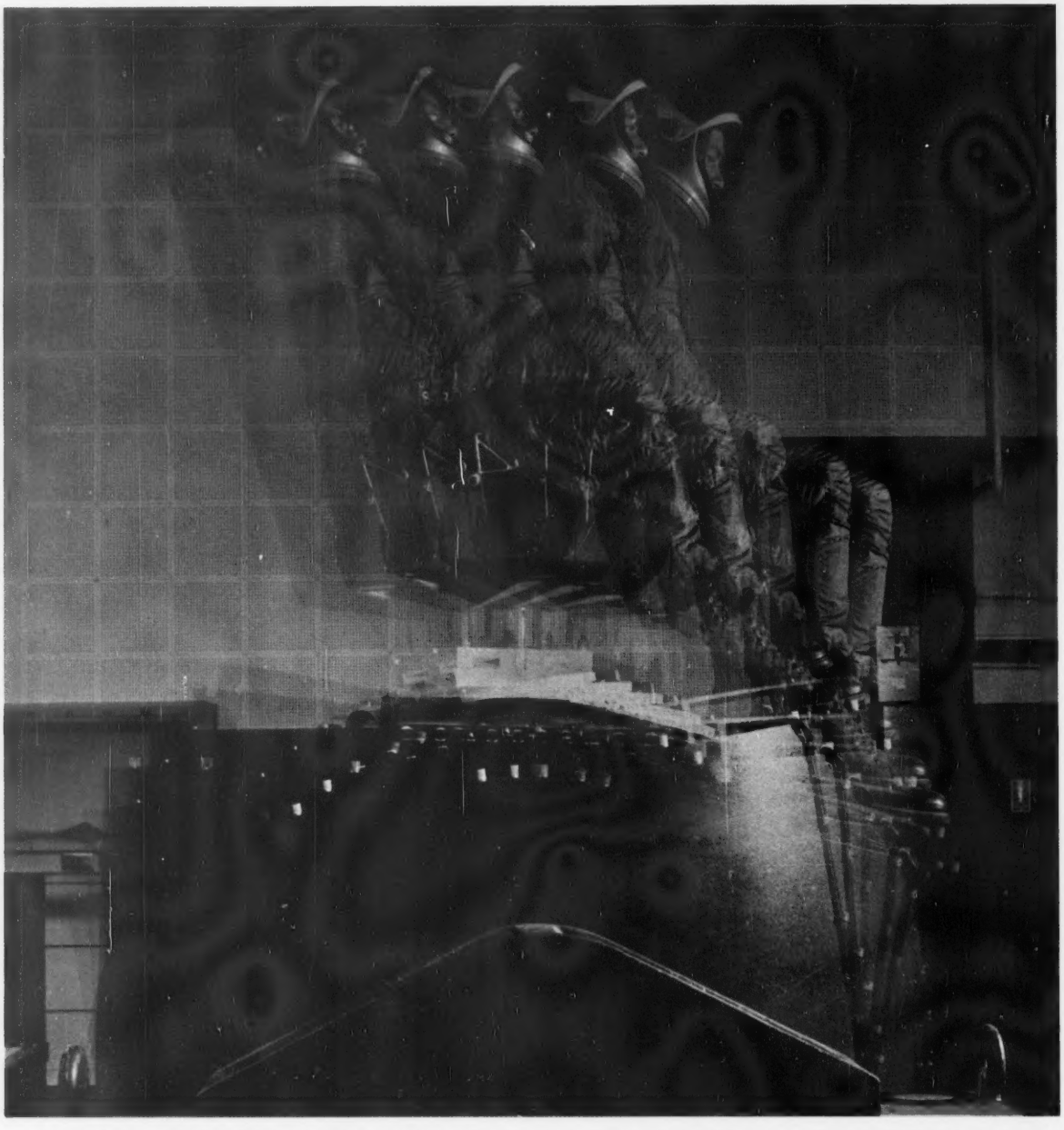

LING SYSTEMS USED BY BOEING TO SHAKE DOWN HUMAN FACTORS AND THE MINUTEMAN

Two modern Minutemen—man and missile—advance guards of the space-age, have taken this shattering ride on a Ling Shaker. The Boeing Airplane Company, as prime contractor on the Minuteman Program, is making extensive use of its complete Ling Vibration Systems to test assemblies for the solid-propellent ICBM. In other studies related to human factors, Boeing researchers checked out man's resistance to the punishing 28,000 lb. force of a Ling A249 Shaker—one of the few available shakers of sufficient size and force to make the experiment practical. The Ling system used by the Boeing Aero-Space Division for these tests is one of the largest systems ever built for random-sine wave testing. The installation reflects the emphasis Boeing places on vibration testing as a key factor in reliability. For details on Ling Vibration Systems which can help you to greater testing reliability, please write Dept. 0000 at our Anaheim address.

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